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EXPLORING ASSYMETRIES IN CIRCUMSTELLAR ENVIRONMENTS:

Winds, Disks, and Things that Go Clump in the Light

NASA Grant NAG5-6039

Final Report

For the period 1 March 1997 through 30 September 2001

Principal Investigator

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February 2002

Prepared for

National Aeronautics and Space Administration

Washington, D.C. 20546

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The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

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Exploring Asymmetries In Circumstellar Environments:
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Principal Investigator: Kenneth Wood
Host Institution: Smithsonian Astrophysical Observatory

The aim of the NASA LTSA Grant NAG 5-6039 was to develop Monte Carlo radiation transfer techniques for use in the analysis of data from stellar systems that exhibit evidence for extended, non-spherical circumstellar environments. The broad applicability of the codes I have developed has opened many new research areas to me, as is reflected by the range of topics covered in the bibliography.

Code Development
Code development fell into the three broad categories summarized below: scattered light; radiative equilibrium; ionization equilibrium.

The *scattered light* codes developed are fully three dimensional running on Linear Cartesian and now spherical polar grids. The Linear Cartesian grid code has been made available to several collaborators and is now available via a FTP site. In addition to simulating scattered light images from stellar and diffuse sources of emission, the code now includes the effects of Doppler broadening on scattered lines due to bulk and thermal motions of the source-scatterers-observer. This new addition is being used for projects to model scattered emission lines in the Milky Way's Interstellar Medium and to determine the effects of scattering on galaxy rotation curves.

The *radiative equilibrium* codes have been tested against several standard test cases and papers describing the technique and application to protoplanetary disks have been published. These codes will also be made public and will be important for the analysis and modeling of forthcoming SIRTF spectra and mid-IR imaging data.

A code that calculates the 3D *ionization balance* of hydrogen has been developed and applied to the study of the escape of ionizing radiation from galaxies. Projects are underway to apply the ionization code to the study of clumpy H II regions.

Star Formation: Circumstellar Disks and Protostellar Envelopes
I have published several theoretical papers investigating the observational signatures of the currently favored magnetospheric accretion models for T Tauri stars. Results of a photometric monitoring campaign on the disk source HH 30 IRS were also published. I have conducted detailed 3D radiation transfer modeling of several protostellar sources imaged by HST. The models investigated the effects on image morphology of multiple illuminating sources and envelopes that have been shaped by multiple outflows.

Papers modeling the spectral energy distributions (SEDs) from protoplanetary disks have been published. Our scattered light and SED models provide further evidence for grain growth within disks. We have also interpreted the range of disk colors in Taurus-Auriga sources in terms of simple disk evolution models. SIRTF surveys of clusters will enable us to further test and refine our models and understanding of disk evolution. Our Monte Carlo codes will be extemely useful for interpreting data from the SIRTF mission.

Spectropolarimetry of Hot Star Winds
I have published a series of papers describing the effects of multiple scattering on the emergent polarization specta from rapidly rotating Be star disks. We have also developed techniques to determine the geometry of Be star disks from modeling combined optical spectropolarimetry and far-IR excess emission. A paper has been submitted that describes a technique for using UV spectropolarimetry to determine ionization temperatures within Be star disks. We are continuing to

apply our modeling techniques to the large spectropolarimetric database obtained by the WUPPE mission and from the NASA funded spectropolarimeter at Pine Bluff Observatory.

Resonant Line Scattering in Coronal Loops and Supernova Remnants

With John Raymond (CfA) I have investigated the effects of resonant scattering of emission lines on the image morphology and intensity from coronal loop structures. Our simulations show that intensity variations across images are more uniform than optically thin simulations. In addition, depending on viewing angle, the intensity may be lower or higher than that predicted from optically thin simulations due to scattering out of or into the line of sight. I have also applied this modeling technique to the analysis of HST/STIS imaging spectroscopy of supernovae remnants with Ravi Sankrit (Johns Hopkins).

More recently I have extended the coronal models to predicting X-Ray emission and variability from cool star coronae. For this project I take coronal magnetic and plasma density models derived from analysis of Zeeman Doppler Imaging maps. The resulting X-Ray emission from the coronal plasma is calculated with my 3D Monte Carlo codes for comparison with time resolved X-Ray data from Chandra and XMM-Newton. This project is in collaboration with Andrew Cameron and Moira Jardine (St Andrews).

Galactic and Extragalactic Astronomy and Cosmology

With Terry Jones (Minnesota) I have investigeted polarization patterns in spiral galaxies due to scattering and transmission through dust grains aligned by large scale galactic magnetic fields. The level of scattered Hα light in the Milky Way's Warm Ionized Medium has been modeled in collaboration with Ron Reynolds (Wisconsin). New data from the Wisconsin Hα Mapper (WHAM) at both Hα and Hβ will be modeled using the scattered light code that includes Galactic velecity structures, described above.

Together with Lynn Matthews (NRAO), we have used a combination of my Monte Carlo techniques and multi-color ($BRIJHK$, Hα) imaging data to investigate the nature of the interstellar medium (morphology and kinematics) in the edge-on, low surface brightness (LSB) galaxy UGC 7321. Our models are some of the first with sufficient resolution and signal-to-noise to explore the low optical depths encountered in LSB galaxies.

With Avi Loeb (Harvard) I have calculated the steady-state escape fraction of ionizing photons from disk galaxies as a function of redshift and galaxy mass. The sources of radiation are taken to be either stars embedded in the disk, or a central quasar. The predicted increase in the disk density with redshift results in an overall decline of the escape fraction with increasing redshift. For typical parameters of smooth disks, we find that the escape fraction at $z \sim 10$ is $< 1\%$ for stars, but $> 30\%$ for mini-quasars. Unless the smooth gas content of high-redshift disks was depleted by more than an order of magnitude due to supernovae-driven outflows or fragmentation, the reionization of the universe was most likely dominated by mini-quasars rather than by stars.

What's Next...?

Now that my NASA LTSA has ended, I have been very fortunate to have obtained a faculty position at the University of St Andrews, Scotland. Here I am continuing to develop and extend the capabilities and scope of my Monte Carlo techniques. I have embarked upon collaborations with the cool star (Moira Jardine, Andrew Cameron) and star formation (Ian Bonnell, Phil Armitage) groups at St Andrews. As I mentioned earlier, I have started making my Monte Carlo codes publicly available at http://www-star.st-and.ac.uk/ kw25/. I have also ensured that my collaborations with US colleagues will continue. The fact that my office is a five minute walk to the first tee of the Old Course ensures that I have a steady stream of visiting collaborators!

If anyone is actually reading this report, I'd like to thank NASA for funding my research in the USA for the last five years. It was a fantastic experience, I learned lots, made so many friends and collaborators, and simply had a great time. I hope that I have lived up to my end of the deal through publishing papers and now making the codes publicly available.

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